Effect of Clouds on the Diffuse Component of the Solar Terrestrial Erythemal UV

D. J. Turnbull*, A. V. Parisi and N. J. Downs

Faculty of Sciences, University of Southern Queensland, Toowoomba, 4350, Australia.

Ph: +61 7 46 311488. Fax: +61 7 46 311530.

Email: turnbull@usq.edu.au

**To whom correspondence should be addressed*

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Abstract
Broadband diffuse erythemal UV (SUV) and cloud cover were measured at five minute intervals for a 12 month period at a Southern Hemisphere site and for a solar zenith angle (SZA) range of 5^o to 80^o. Measured data for cloud conditions of 1 to 7 okta showed that variation in diffuse SUV due to cloud compared to modelled clear sky diffuse SUV, ranged from 0.8 to 1.2 for an SZA of 10^o, 0.8 to 1.54 for 40^o, and 0.9 to 1.8 for 70^o. An empirical non-linear expression as a function of SZA has been developed for cloudy sky conditions of 1 to 7 okta to allow the evaluation of the diffuse SUV. The percentage of occurrences of the times required for an exposure of 1 standard erythemal dose (SED) due to the diffuse SUV for all sky conditions was a maximum in the range of 10 to 20 minutes with an occurrence of 32.1%, followed by 20.0% for 20 to 30 minutes, and 19.5% for 30 to 60 minutes. For the cases when the diffuse SUV was enhanced above that of modelled clear sky conditions for cloud cover of 1 to 8 okta, the maximum incidence for an SED was in the range of 10 to 20 minutes with an occurrence of 32.4%, followed by 19.9% for 20 to 30 minutes.

Keywords: Diffuse; SUV; Erythema; Cloud

1. Introduction

UV radiation incident on the Earth's surface is comprised of both a direct and diffuse component [1]. As the direct component is incident directly from the sun, it is easy to minimize by simply blocking its path. However, the diffuse UV component is incident from all directions due to atmospheric scattering and is difficult to reduce [1]. For a completely overcast sky, all radiation is considered as diffuse radiation [2]. The ratio of diffuse UV to direct UV varies with both wavelength and solar elevation for clear sky conditions [2]. These differences are caused by Rayleigh scattering ($\propto \frac{1}{\lambda^4}$) and Mie scattering ($\propto \frac{1}{\lambda}$) in the atmosphere, which causes greater scattering at the shorter UVB (280-315 nm) wavelengths compared to the longer UVA (315-400 nm) wavelengths. The dependency of direct and diffuse UV wavelength scattering with solar elevation similarly influences the biologically effective exposure received due to the variation in wavelength dependency of different action spectra [3].

Ozone, clouds and a changing solar zenith angle influence significantly the attenuation of biologically damaging UV at ground level [4,5]. Erythemal UV (SUV) irradiances are generally strongly influenced by cloud [5]. Particular configurations of cloud can increase UV levels above that on a cloud-free day [6,7]. Bais et al [8] found that overcast skies were capable of attenuating UV in the wavelength range of 290 to 325 nm, by as much as 80%, irrespective of wavelength. Sabburg and Wong [6] reported that 3% of UVB irradiance measurements (over an entire year) were cloud enhanced. In addition, it was found that 85% of these enhancements occurred for a range of SZA's from 40^o to 63^o. Sabburg et al [9] reported marginally higher UV enhancements and frequency in the UVB compared to the UVA. Sabburg et al [9] also found that UV enhancements were wavelength independent for wavelengths longer than 306 nm and increasingly wavelength dependent for shorter wavelengths. Parisi and Downs [7] reported that the relative UVA to UVB effectiveness of the action spectra for the biologically damaging process influenced the observation of the cloud enhanced UV, with more enhancement occurring for action spectra with a higher relative effectiveness in the UVB waveband.

Numerous theoretical, semi-empirical and empirical mathematical approaches have been used to describe the effect of cloud on clear sky irradiances. The first model was put forward by Buttner [10], with a simple UV-cloud relationship. Since then a number of models have tried incorporating cloud properties into the equations (for example, 11-15). However, the incorporation of varying cloud levels into current theoretical global UV models remains an ongoing process. The incorporation of cloud cover into diffuse UV models has also been conducted. Previous research by Grant and Gao [16] produced two models to calculate diffuse UVB and UVA under partly cloudy skies. Weihs et al [17] compared radiance distribution measurements under broken cloud conditions to clear sky modelled data and found good agreement to Grant et al [18] for scattering angles larger than 40^o.

Diffuse UV constitutes a significant contribution of the UV exposure to human eyes and skin, as it is incident from all directions and difficult to minimize with the usage of hats and shade environments [19]. Consequently, a greater emphasis has been placed on reducing human exposure to the diffuse component of incident terrestrial ultraviolet radiation (e.g. 1,20-24). This paper extends previous research by developing an empirical non-linear expression for the evaluation of diffuse SUV and a changing cloud level of 1 to 7 okta, and also illustrating that varying cloud cover can enhance diffuse SUV levels above that for clear sky conditions.

2. Materials and Methods

2.1 Measurement site

The measurement site for this research was the campus of the University of Southern Queensland (USQ), Toowoomba, Australia (27.6^{o}S, 151.9^{o}E, altitude 692 m a.s.l.). The instruments were mounted on an unobstructed roof at the USQ campus. The daily atmospheric column of ozone as obtained from the TOMS (Total Ozone Mapping Spectrometer) ranged from 243.5 to 337.0 DU over the twelve month measurement period from January to December 2003.

2.2 Diffuse Erythemal UV measurements

An erythemal UV meter (UV-Biometer Model 501 Version 3, Solar Light Co., Philadelphia, PA) was employed to monitor the diffuse SUV. The diffuse SUV meter is a global SUV meter that has been specifically set up to measure the diffuse erythemal radiation. It utilizes a shadow band, which is aligned east-west, to block the sun during the day. The shadow band is 0.076 m wide and the distance from the shadow band to the top of the diffuse SUV meter varies from 0.25 m to 0.27 m as it is moved with the seasons. The shadow band blocks out part of the sky view and this has been measured at approximately 10%. A correction has been applied to all of the data to account for this.

The diffuse SUV meter was set up to record data every five minutes. The meter is temperature stabilized to 25^{o}C and calibrated twice a year during clear sky conditions against a scanning spectroradiometer (described below).

The scanning UV spectroradiometer (model DTM300, Bentham Instruments, Ltd, Reading, UK) employed to calibrate the diffuse SUV meter is based on a double grating monochromator, a UV sensitive detector and amplifier with software variable gain provided by a programmable high voltage power supply. The spectroradiometer is housed in an envirobox that employs a Peltier cooler unit to stabilise the enclosure to 23.0 ± 0.5 ^{o}C. A PTFE (polytetrafluoro ethylene) diffuser connected by an optical fibre to the input slit of the monochromator provides the input optics. The manufacturer determined error associated with the cosine response of the diffuser is stated as less than ±0.8% for a SZA up to 70^{o} and 3.3% for a SZA of 80^{o}. This spectroradiometer is calibrated against a 150 W quartz tungsten halogen lamp with calibration traceable to the National Physical Laboratory, UK standard and wavelength calibrated against the UV spectral lines of a mercury lamp**.**

2.3 Cloud Measurement

The amount of cloud cover was quantified with the use of the Total Sky Imager (TSI) (model TSI-440, Yankee Environmental Systems, MA, USA). The TSI is currently mounted on top of a university building near the diffuse SUV meter and is set up to automatically collect data for SZA less than 80^o and to process this data to provide the fraction of cloud cover. The TSI has a charge coupled device (CCD) camera and software package that captures images into JPEG format data files, which are then analysed for fractional cloud cover. Overload of the CCD is prevented by use of a shadow band that tracks the sun's movement to obscure the solar disc on the mirror. The CCD camera is mounted over the mirror by a thin pipe. The shadow band and camera support are masked in the image processing and subsequently not included in fractional cloud cover estimates. The system provides the percentage of cloud cover reading during all daylight hours with SZA less than 80^o, at a user-defined interval of 5 minutes. For this paper, the percentage of cloud cover was converted to the amount of cloud cover in oktas.

3. Results and Discussion

3.1 All Sky Conditions Diffuse SUV

Variation in the diffuse SUV irradiances for all sky conditions and a changing SZA are shown in Figure 1. The data in Figure 1 corresponds to over 15,700 data points when both the diffuse SUV meter and TSI were operational. For a SZA of approximately 5^o, observed maximum and minimum diffuse SUV levels were 0.193 W/m^2 (6.95 SED/hr) and 0.064 W/m^2 (2.30 SED/hr), respectively. A standard erythemal dose (SED) is equivalent to 100 J/m^2 [25]. For the larger SZA of approximately 70^o, maximum and minimum SUV levels of 0.027 W/m^2 (0.97 SED/hr) and 0.004 W/m^2 (0.14 SED/hr) were observed. Modelled clear sky diffuse SUV data for 2003 based on a previously described model [26] has been placed on top of the measured data to illustrate the comparison of the modelled to measured data for a changing SZA of 5^o to 80^o.

3.2 Cloud Cover and Diffuse SUV

From over 15,700 data points collected, approximately 7,800 data points were classified as having a cloud cover ranging from 1 to 8 okta. As shown in Figure 2a and b, this data has been broken down into separate cloud levels of 1 to 7 okta and 8 okta, respectively. This was undertaken as the 1 to 7 okta of cloud cover has a lesser effect on the diffuse SUV compared to 8 okta of cloud. The following regression curve was fitted to the diffuse SUV data, in Figure 2a, with a resulting R^2 of 0.95:

$$\textit{Diffuse SUV} = 5.0\text{x}10^{-7}(SZA)^3 - 7.5\text{x}10^{-5}(SZA)^2 + 7.7\text{x}10^{-4}(SZA) + 1.6\text{x}10^{-1}\ \text{W/m}^2 \quad (1)$$

This regression model does not differentiate between cloud type, cloud height or optical depth.

Figure 3 shows the differences between the regression model and the corresponding actual measurements for a changing SZA. Analysis of the data shows that approximately 95% of the measured data was within a maximum range of ± 0.025 W/m^2 of the regression model. Previous research by Grant and Gao [16] produced two models to calculate diffuse UVB and UVA under partly cloudy skies with a maximum R^2 of 0.87.

The research presented extends this by producing a regression model for diffuse erythemal UV under cloud conditions of 1 to 7 okta and an R^2 of 0.95.

Figure 4 illustrates the agreement between the measured cloudy sky conditions of 1 to 7 okta and the modelled clear sky data shown in Figure 1. Measured data for cloud conditions of 1 to 7 okta showed that variation in diffuse SUV due to cloud when compared to clear sky modelled data ranged from 0.8 to 1.2 for an SZA of 10^o, 0.8 to 1.54 for 40^o, and 0.9 to 1.8 for 70^o. This shows that cloud cover can significantly increase diffuse SUV above that for clear sky conditions.

Figure 5a shows the percentage of occurrences of the times required for an exposure of 1 SED due to the diffuse SUV for all sky conditions. The maximum incidence for an SED was in the range of 10 to 20 minutes with an occurrence of 32.1%, followed by 20.0% for 20 to 30 minutes, and 19.5% for 30 to 60 minutes. An exposure time of less than 10 minutes for an SED resulted from only 2.6% of the data. Figure 5b shows the percentage of occurrences of the times required for an exposure of 1 SED due to the diffuse SUV, for the cases when it was enhanced above that of modelled clear sky conditions for cloud cover of 1 to 8 okta. The maximum incidence of the times for an SED was in the range of 10 to 20 minutes with an occurrence of 32.4%, followed by 19.9% for 20 to 30 minutes, and 18.7% for 30 to 60 minutes. An exposure time of less than 10 minutes for an SED resulted from 7.6% of the data.

4. Conclusion

With more emphasis being placed on the diffuse component of incident terrestrial ultraviolet radiation and human exposure, more research is needed to better explain how diffuse UV varies according to variation in atmospheric and environmental conditions. A number of factors influence the levels of diffuse UV that humans are exposed to, namely clouds, surface albedo, solar zenith angle, amount of sky view and atmospheric particles and aerosols. For cloudy skies of 1 to 7 okta and surfaces not covered by high albedo coverings, namely snow, diffuse SUV levels can be predicted employing the relevant expression developed in this research to evaluate the diffuse SUV as a function of SZA.

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Figure Captions

Figure 1. Diffuse SUV irradiances as a function of SZA for all sky conditions. The open symbols are the modelled clear sky values.

Figure 2. Diffuse SUV irradiances for (a) 1 to 7 okta of cloud cover and (b) 8 okta of cloud cover as a function of SZA.

Figure 3. Differences between the fitted regression model and the measured cloudy sky data for cloud conditions of 1 to 7 okta.

Figure 4. Ratio of measured diffuse SUV and modelled clear sky diffuse SUV for a changing SZA.

Figure 5. The percentage of occurrences within a certain time range of the time required for an exposure of 1 SED due to diffuse SUV for (a) all sky conditions and (b) due to diffuse SUV for the cases when it was enhanced above that of modelled clear sky conditions for cloud cover of 1 to 8 okta.

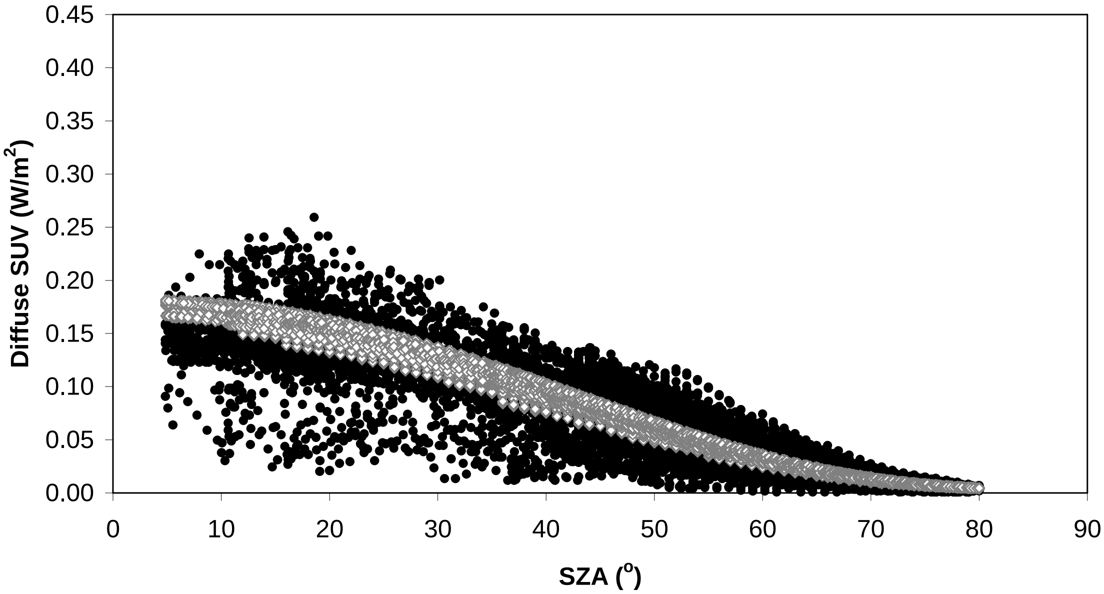
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Diffuse SUV (W/m2)
0
10
20
30
40
50
60
70
80
90
SZA (o)

Figure 1.

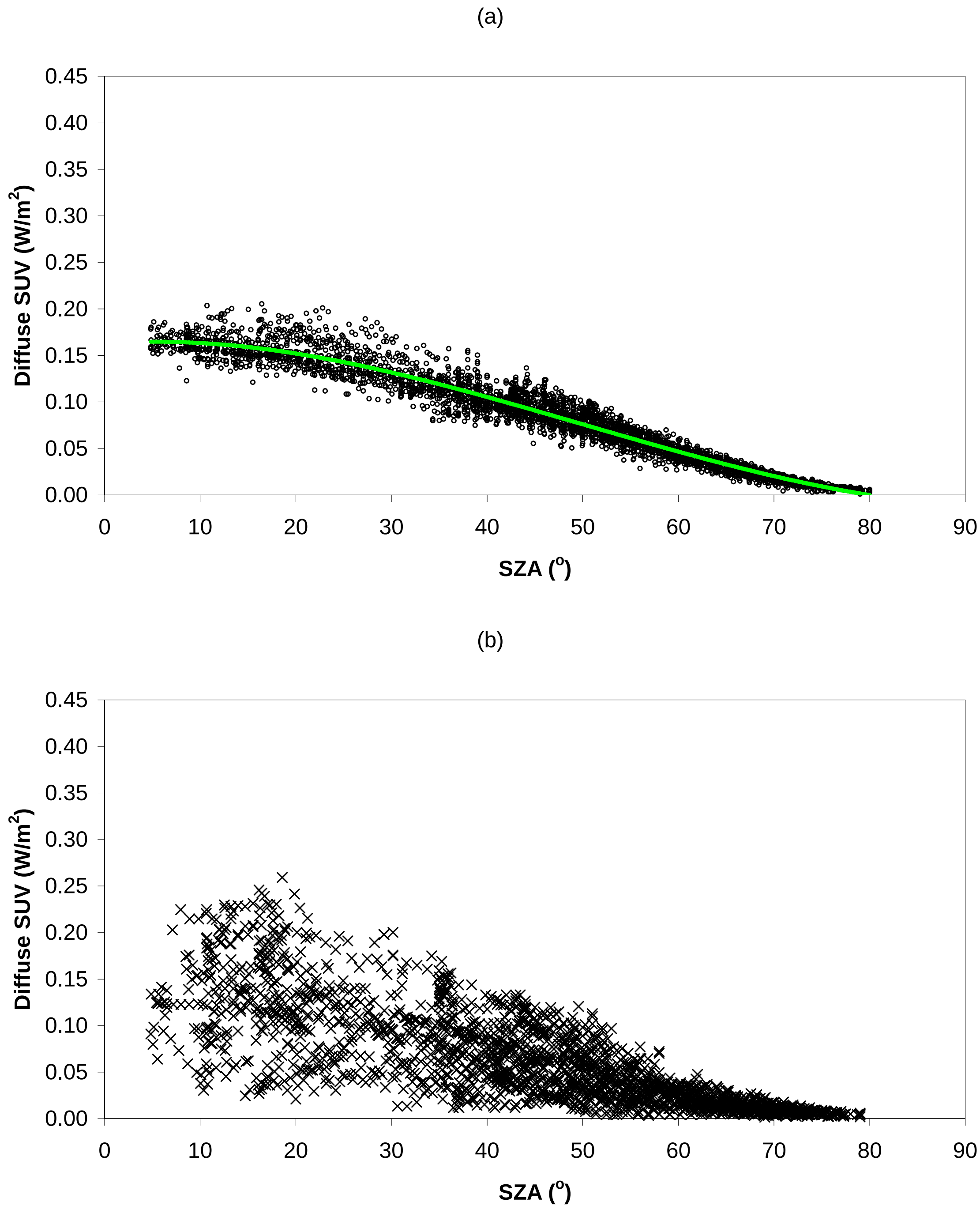
(a)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Diffuse SUV (W/m2)
0 10 20 30 40 50 60 70 80 90
SZA (o)
(b)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Diffuse SUV (W/m2)
0 10 20 30 40 50 60 70 80 90
SZA (o)

Figure 2.

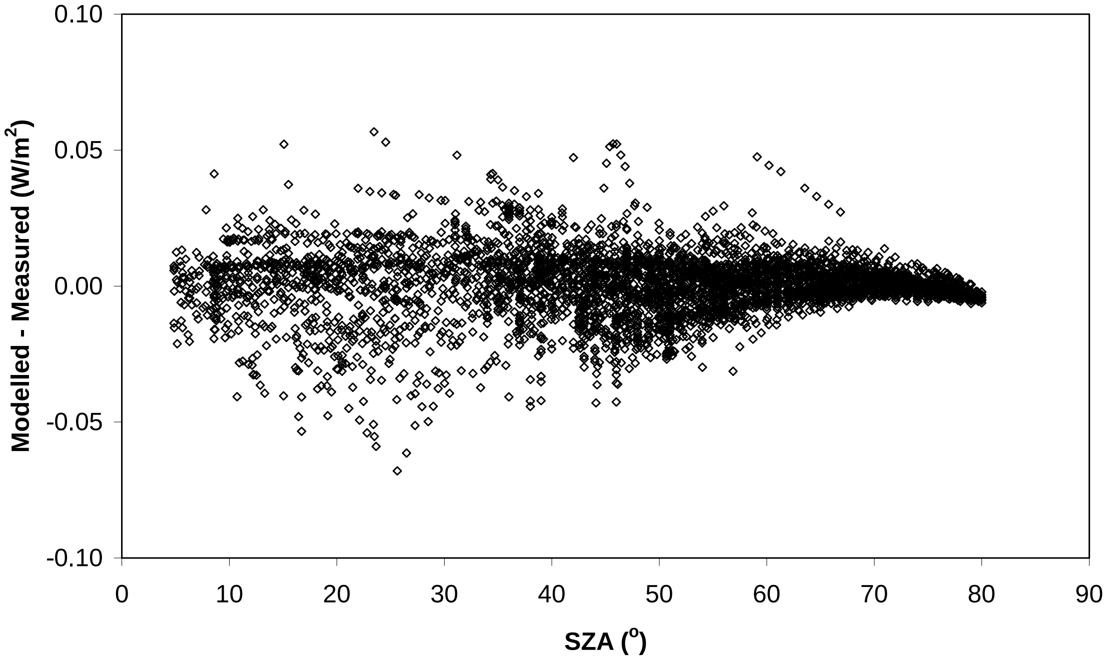
0.10
0.05
0.00
-0.05
-0.10
Modelled - Measured (W/m2)
0
10
20
30
40
50
60
70
80
90
SZA (o)

Figure 3.

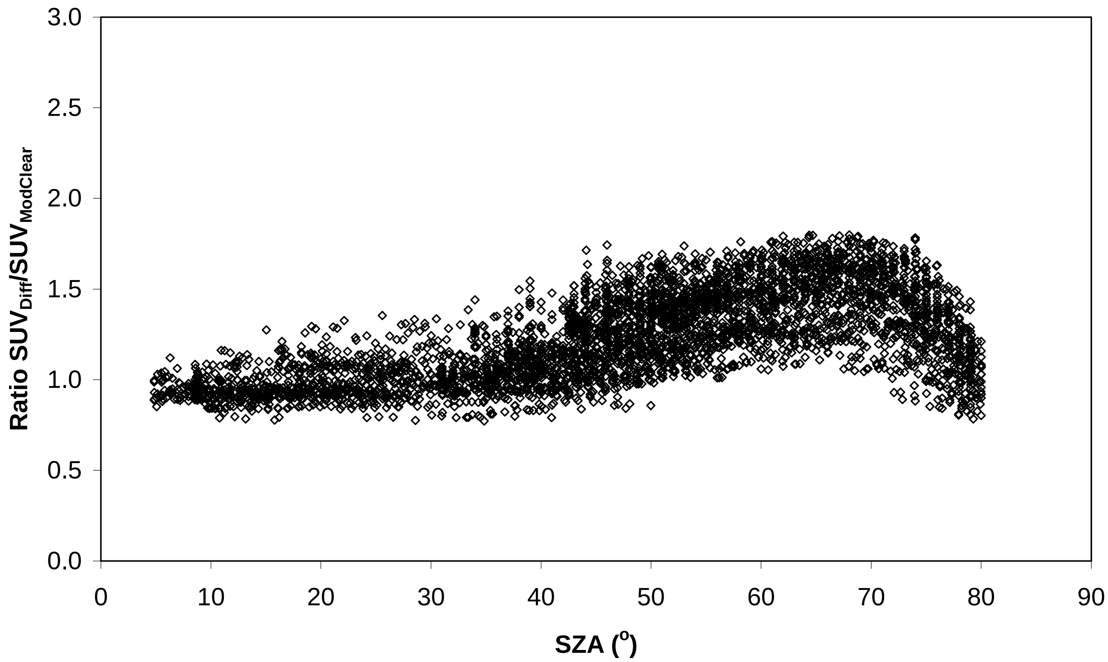
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Ratio SUV$_{Diff}$/SUV$_{ModClear}$
0
10
20
30
40
50
60
70
80
90
SZA (^{o})

Figure 4.

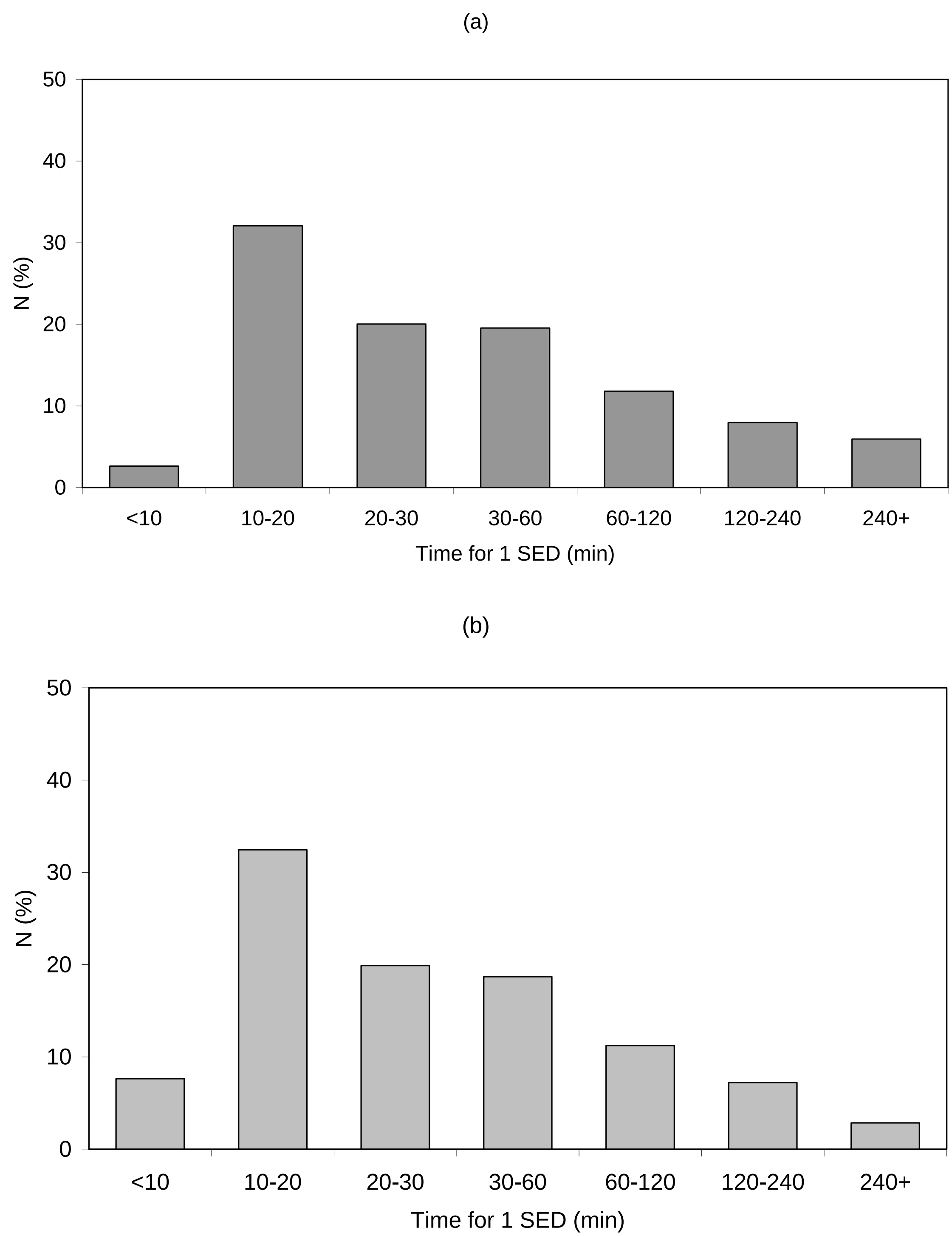
(a)
50
40
30
20
10
0
N (%)
<10
10-20
20-30
30-60
60-120
120-240
240+
Time for 1 SED (min)
(b)
50
40
30
20
10
0
N (%)
<10
10-20
20-30
30-60
60-120
120-240
240+
Time for 1 SED (min)

Figure 5.